Impacts of Turbulence on Hurricane Intensity

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LONG-TERM GOALS

Our recent studies have shown that hurricane boundary layer turbulence, which must be *parameterized* in the current-generation weather-prediction models, plays a significant role in controlling the hurricane intensity. We find that *horizontal* turbulence, particularly in the radial direction (i.e., towards or away from the hurricane center), plays an important role in regulating hurricane intensity. The long-term goal of this project is thus to improve the hurricane intensity forecast by developing a more physically based horizontal turbulence parameterization scheme for hurricanes.

OBJECTIVES

The effects of turbulence on simulated hurricanes can be quantified if the turbulence is resolved in the numerical model. Thus, one objective of the current project is to perform a set of large-eddy simulations (LES) with increasing resolution (grid spacing as small as ~50 m) until the bulk statistics such as maximum intensity and turbulence eddy fluxes are converged. These simulations will then be analyzed to estimate eddy-diffusion coefficients for use in weather-prediction models.

APPROACH AND WORK PLAN

Because of the multi-scale nature of hurricanes, the proposed large-eddy simulation work is a challenging computational problem. A three-dimensional research cloud model (CM1) with horizontal grid stretching capability is being configured for the convergence test. In addition, the Weather Research and Forecasting (WRF) model (ARW core) is being used as a weather-prediction model to examine the eddy-diffusion coefficients obtained from CM1 simulation in both idealized and real-data hurricane cases.

The PI, Dr. Yongsheng Chen, will analyze the existing high-resolution WRF simulations, implement the findings from WRF and CM1 simulations in new real-data WRF retrospective forecasts, and supervise a graduate student as part of this project.

Dr. George Bryan, the developer of CM1 model, will conduct numerical simulation and analysis of idealized hurricanes using the CM1 model.

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Dr. Richard Rotunno will synthesize WRF and CM1 simulations and design a new radial-turbulence parameterization scheme for weather-prediction models with typical resolution of O(1km).

Effects of turbulence mixing length scales and surface exchange coefficients on the hurricane intensity at typical model resolutions were systematically conducted using CM1 and compared to recent observational studies. The sensitivities of hurricane intensity, structure and its environment to changes in the horizontal turbulence mixing length scale and horizontal resolution were studied using WRF for a real hurricane case.

In the coming year, the generality of CM1 results at typical resolution of O(1km) will be tested by adding other physical parameters including hurricane translational motion and varying SST.
Based on the turbulence mixing length scales that will be determined from large-eddy simulations of WRF and CM1, a parameterization scheme of turbulence horizontal mixing length scale will be designed and tested in WRF simulations.

WORK COMPLETED

A large number of simulations (~1000 total simulations) were conducted using CM1 with 1-km horizontal grid spacing to test the effects of turbulence length scale (l_h and l_v) and ratio of surface exchange coefficients for enthalpy and momentum (C_k /C_d). A journal article is in press (Bryan 2011). The optimal settings from this part of the project are now being used in the 3d coarse-resolution mesh simulations that will provide the lateral boundary conditions for the large eddy simulation (LES) fine-mesh domain. Another journal article that studies the problem theoretically, and compares to classic analytical vortex-boundary-layer solutions, has been submitted to *J. Atmos. Sci* (Rotunno and Bryan, 2011).

The impact of changing horizontal turbulence mixing length scale (l_h) on the hurricane intensity, structure, and its environment were investigated using WRF model in numerical simulations of Hurricane Earl (2010). The results, if accepted, will be presented in 2012 AMS Conference on Hurricane and Tropical Meteorology.

RESULTS

A set of simulations of idealized hurricanes using the CM1 model has examined the sensitivity of hurricane intensity and structure to changes in the surface exchange coefficients and to changes in the length scales of a turbulence parameterization. Compared to other recent articles on the topic, this study used higher vertical resolution, more values for the turbulence length scales, a different initial environment (including higher sea surface temperature), a broader specification of surface exchange coefficients, a more realistic microphysics scheme, and a set of three-dimensional simulations. The primary conclusions from a recent study by Bryan and Rotunno are all upheld: maximum intensity is strongly affected by the horizontal turbulence length scale (l_h) but not by the vertical turbulence length scale (l_v); and, the ratio of surface exchange coefficients for enthalpy and momentum, C_k/C_d , has less effect on maximum wind speed than suggested by an often-cited theoretical model. The model output is further evaluated against various metrics of hurricane intensity and structure from recent observational studies, including: maximum wind speed, minimum pressure, surface wind-pressure relationships, height of maximum wind, and surface inflow angle. The model settings $l_h \approx 1000$ m, $l_v \approx$

50 m, and $C_k/C_d \approx 0.5$ produce the most reasonable match to the observational studies, and thus will be used for the relatively coarse resolution ($\Delta x = 1$ km) 3d simulations that provide the lateral boundary conditions to the LES simulations.

In addition, results from numerical simulations of Hurricane Earl (2010) using the WRF (ARW) model are consistent with the idealized simulations using CM1 model. Earl is a strong Category 4 hurricane whose maximum wind (v_{max}) at peak intensity is 125 knots (64 m/s). Utilizing the storm-following and quadruply nested domains with horizontal resolutions of 36-12-4-1.33 km, the WRF model produces a good forecast with a maximum intensity at 69 m/s. The intensity is reduced with reduced horizontal resolution. The default turbulence horizontal mixing length (l_h=c_s*Δx, c_s=0.25) is only about 330m for the finest domain, much smaller than the suggested value from CM1 simulation. When c_s is increased to 1.0 for all the domains (l_h=1.33 km for the finest domain), the maximum wind is reduced dramatically to 51 m/s, the eyewall becomes larger and slopes more gently. It is further found that varying c_s in simulations with a single 36-km domain can also lead to significant changes in maximum wind (e.g., v_{max} increases from 36 m/s to 51 m/s when c_s is changed from 0.25 to 0.1). While Hurricane Danielle and Tropical Storm Fiona covered in the coarse domain have better intensities by setting an uniform value of l_h =1800 m, Hurricane Earl does not gain enough intensity comparing to the default simulation. These results suggest that a more physically based turbulence parameterization scheme is necessary to improve hurricane intensity forecast.

IMPACT AND APPLICATIONS

Quality of Life

The ultimate goal of this study is to improve hurricane prediction. Accurate hurricane track and intensity forecasts are crucial to effective protection of people and property.

Specifically, our current results are significant because they have a direct impact on how real-time hurricane forecasting models are designed. The horizontal turbulence parameterization in real-time models is usually configured based on trial-and-error or from theoretical studies that may not apply to hurricanes (e.g., Smagorinsky 1963). Our work is leading towards a physically justifiable turbulence parameterization for real-time models, such as the WRF model that is being used by researchers and forecast centers world-wide.

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